Specific heat capacity measurement of *Phyllostachys edulis* (Moso bamboo) by differential scanning calorimetry

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Abstract

This study measured the specific heat capacity of *Phyllostachys edulis* (Moso Bamboo) in three directions of the cylindrical coordinate system. The specific heat capacity measurement was conducted by the differential scanning calorimetry (DSC). Results from both internode and node parts of the bamboo culms were presented and compared in this study. Typical results at 25°C were collected for an overall comparison of total specific heat capacity data. A major finding was that the specific heat capacity of the bamboo solid phase increased with the temperature. Relatively small pits, holes and tightly arranged cells resulted in a higher specific heat capacity. In the radial direction, results of both internode and node parts indicated that the specific heat capacity decreased from the external surface to the internal surface. In the tangential and longitudinal directions, average specific heat capacity values exhibited a non-uniform trend. No specific gradients were found in these two directions.

Keywords: Specific heat capacity, Bamboo, DSC

1. Introduction

This study measured the specific heat capacity of the *Phyllostachys edulis* (Moso Bamboo) in three directions of the cylindrical coordinate system. A previous study found that the density and porosity of Moso bamboo varied in these directions (Huang *et al.* 2015). Better understanding the thermal properties in different directions of the bamboo is the foundation for gaining more insights into the heat and moisture transfer mechanism.

Specific heat capacity is a physical property which is defined as the amount of heat required to change a unit mass of a substance by one degree in temperature (Fourier 1878). This property is regarded as an essential input parameter in the mathematical simulation of heat transfer (Maxwell 1872). In the heat conduction equation, the density and specific heat capacity are the two important properties of the energy storage term. See Equation 1.

Bamboo has considerable potential to be utilised as a sustainable building material for the manufacture of window frames and prefabricated wall panels. Relatively high specific heat capacity and density can provide competitive heat storage performance which is important to neutralise the temperature fluctuation of the indoor environment.

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$$k(\nabla^2 T) = \rho C_p \frac{\partial T}{\partial t} \qquad \text{Equation 1}$$

k: thermal conductivity (W/m·K)
T: temperature (K)
ρ: density (kg/m^3)
C_p: specific heat capacity (J/kg·K)
t: time (s)

However, research on the specific heat capacity of bamboo is still in the earlier stage compared to related research on wood. The average specific heat capacity values of dry wood have been investigated by many researchers. These values ranged from 0.962 to 2.114 kJ/kg·K (Volbehr 1896, Beall 1968, Koch 1968, Fasina and Sokhansanj 1996 and Kristijan *et al*. 2014). The estimated specific heat capacity of pellets ranged from 1.074 to 1.253 kJ/kg·K (Guo *et al*. 2013). The specific heat capacity of softwood, softwood bark, and softwood char derived from bark were investigated by DSC. The measured values at 313 K were 1.172 kJ/kg·K, 1.364 kJ/kg·K and 0.768 kJ/kg·K respectively (Gupta *et al*. 2003).

The difficulty of measuring the specific heat capacity of biological building materials, e.g. wood and bamboo, is mainly attributed to their anatomical complexity. Biological building materials are not homogeneous compared to many metals and macromolecular compounds. Previous studies have shown the considerable variation of the density and porosity distribution of Moso bamboo in three different directions (Huang *et al.* 2014). In addition, bamboo is a hygroscopic and porous material with more than one phase. Therefore, the measured specific heat capacity value is considered as the equivalent value.

Specific heat capacity can be measured by indirect methods and direct methods. Indirect methods require other physical properties to calculate the specific heat capacity. The flash method is an effective method to obtain the thermal diffusivity and specific heat capacity if the density of both the specimen and reference material and the specific heat capacity of the reference material are already known (Parker *et al*.1961 and Shinzato and Baba 2001). The direct methods for specific heat capacity measurement are conducted by calorimeters, e.g. adiabatic calorimeters, reaction calorimeters, bomb calorimeters and differential scanning calorimeters (Parker *et al*. 1961, Spink and Wadsö 1976, Cao 1997). Differential scanning calorimeter and modulated differential scanning calorimeter have been utilised in the wood research (Furuta *et al*. 2012, Miki *et al*. 2012). Specific heat capacity measurement by DSC is a quick method with relatively simple working process. The specific heat capacity results can be obtained in wide temperature range rather than a single temperature condition. In addition, The DSC can measure the specimen with relatively small size and the specimen which needs to minimise the influence of water.

Due to the lack of knowledge on the specific heat capacity, the strengths of DSC, and requirements of the heat and moisture simulation on Moso bamboo, this study measured the specific heat capacity of Moso bamboo by DSC. To investigate the variation of the specific heat capacity in different directions of bamboo culms, the measurements were conducted in the radial, longitudinal and tangential directions. The results of this study will be utilised as a physical property database for the future work on the heat and moisture transfer simulation of Moso bamboo. The knowledge of the heat and moisture transfer simulation behaviour is expected to provide a guidance to enhance the thermal performance of bamboo-based building materials.

2. Methodology

2.1 Specimen preparation

The Moso bamboo culms were ordered from the UK Bamboo Supplies Limited. The external diameters of the bamboo culms ranged from 70 mm to 100 mm. The specimens were cut from these culms. The specimens were cut into thin discs to fit the sample chamber of the DSC. The diameter of the discs was 6±0.2 mm. The thickness of the discs was 1±0.2 mm (Fig. 1).

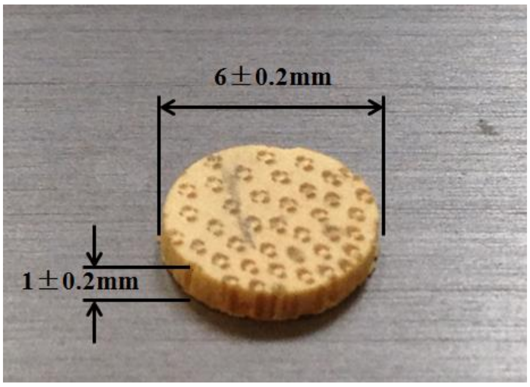


Fig. 1. The dimension of the bamboo specimen.

The specimens were cut from radial, tangential and longitudinal directions at both internode part and node part of Moso bamboo culms. A bamboo culm can be regarded as a cylindrical coordinate system. In this study, three directions of the specific heat capacity, namely radial, tangential, and longitudinal directions, refer to the heat flow directions which are perpendicular to the circular flat surface of the bamboo specimens (Fig. 2).

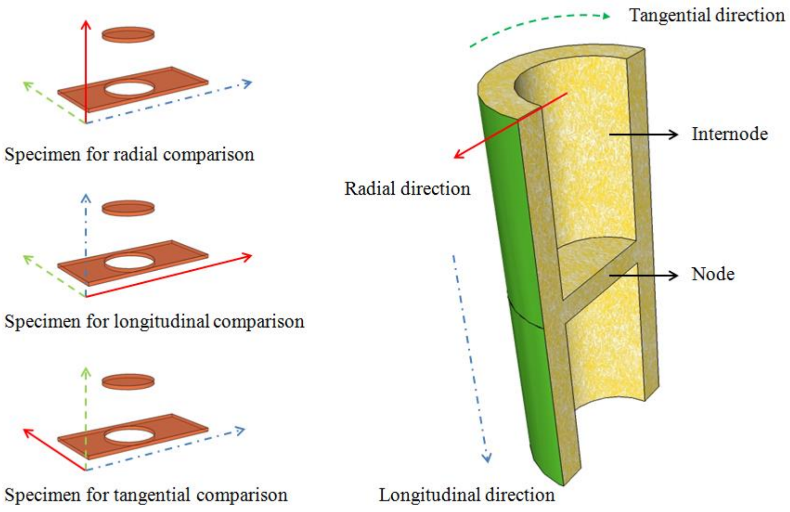


Fig. 2. Nomenclature of the directions of specific heat capacity measurements

In the radial direction, specimens were cut from three positions which refer to the external surface, the middle position and the internal surface of the bamboo culm wall. In the tangential direction, specimens were cut from four positions. An interval of 90° was set between adjacent positions. In the longitudinal direction, specimens were cut from three positions. The distance between two adjacent positions is 10±1 mm in the internode part and 3±1 mm in the node part respectively. This distance is determined by the length of the internode and node parts of bamboo culms. Three specimens were prepared at each position for specific heat capacity measurement (Fig. 3).

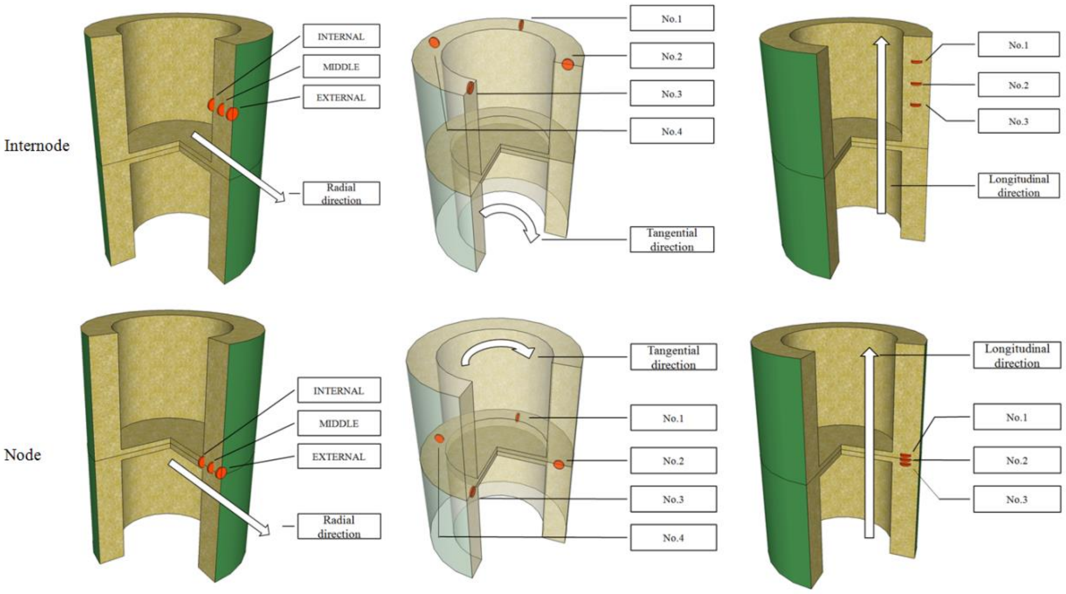


Fig. 3.The cutting positions and numbers of bamboo specimens.

2.2 Specific heat capacity measurement by DSC

The specimens were oven dried to eliminate water at 103 °C. Calcium Chloride ($CaCl_2$) was used as dessicant to store the specimens to avoid moisture absorption. The specific heat capacity was measured using a TA instruments Q200 modulated differential scanning calorimeter with a scan rate of 3 °C/min, a modulation of ±1 °C per 100 s, and an oxygen-free nitrogen gas flow rate of 25 ml/min. Scans were made with the temperature increasing from 5 °C to 40 °C. Specific heat capacity values were extracted from the total heat flow signal.

3. Results and discussions

3.1 Results from three directions

The results are illustrated by bar charts with standard deviations. Both internode and node parts of Moso bamboo specimens are included. The vertical axis represents the specific heat capacity. The unit of the specific heat capacity is kJ/kg·K. The horizontal axis represents the temperature. The temperature ranges from 5 ºC to 40 ºC. This temperature range covers the majority of the service range of building materials. The temperature range from 5 ºC to below 0 ºC is not discussed in this study.

In the radial direction, Moso bamboo specimens were cut from three positions. Three positions refer to the external surface, the midpoint and the internal surface of a bamboo culm wall. Three specimens were measured at each position. The results of both internode and node parts indicate that the specific heat capacity decreases from the external surface to the internal surface. Specific heat capacity values increase with temperature. The difference among three positions is higher at node parts. See Fig. 4 and Fig. 5.

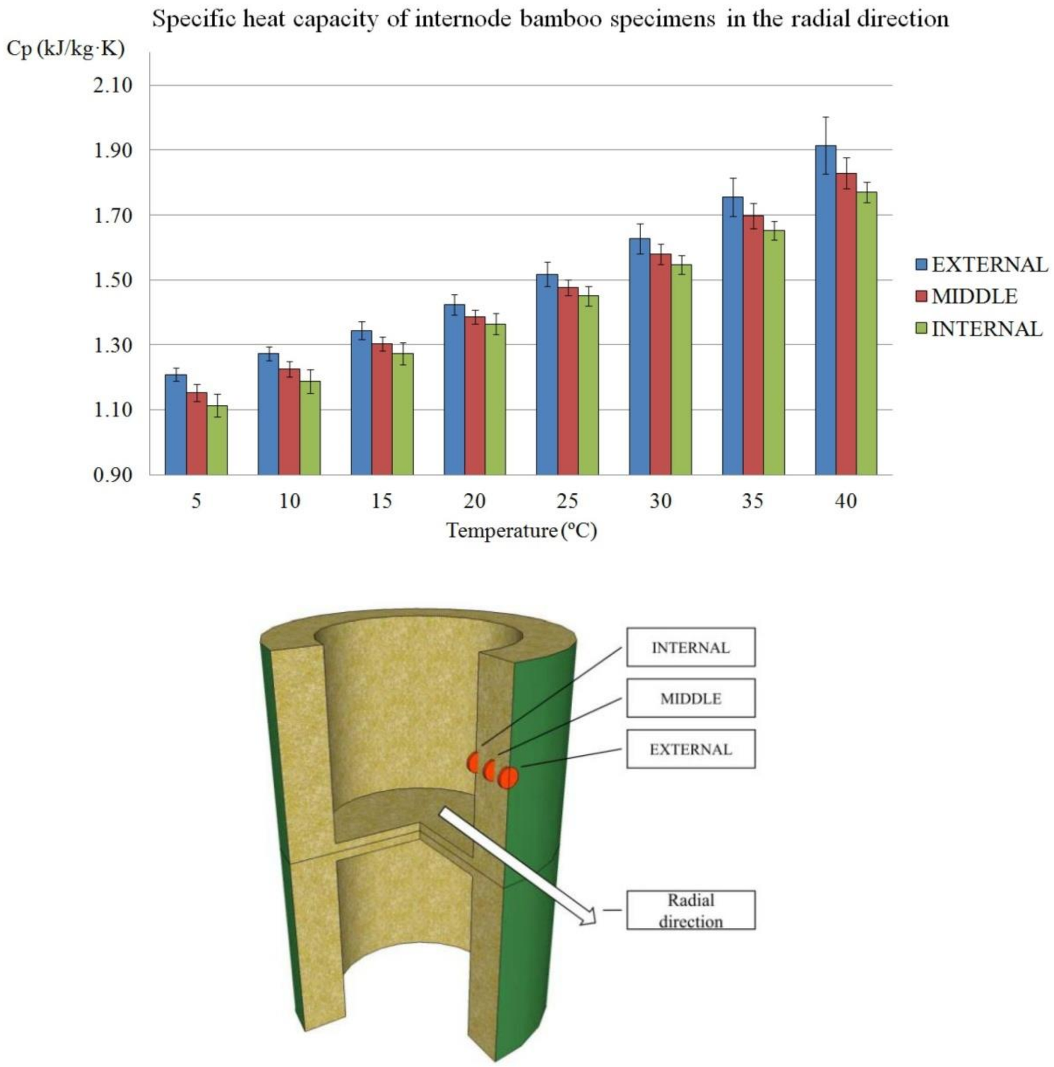
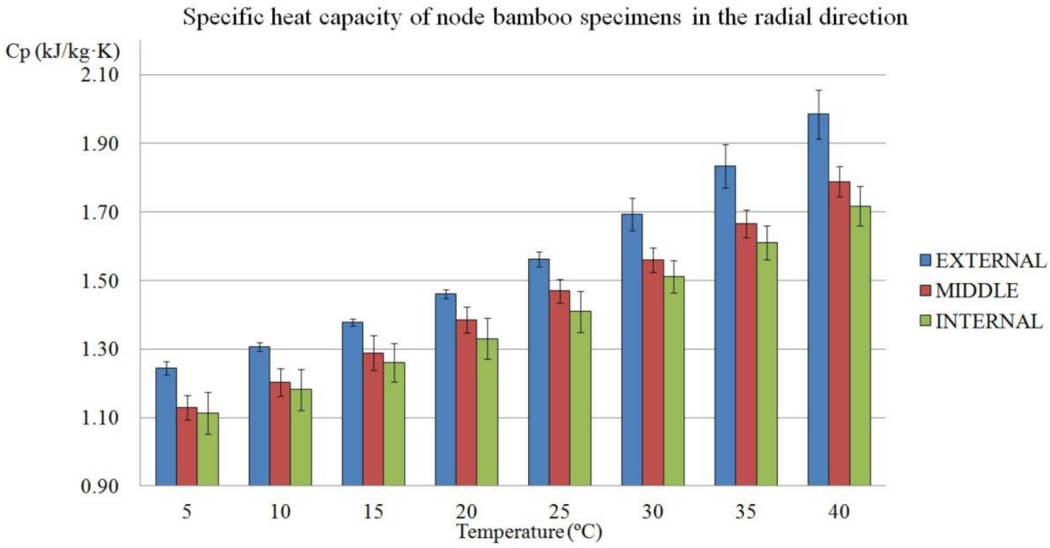


Fig. 4. Specific heat capacity of internode bamboo specimens in the radial direction.



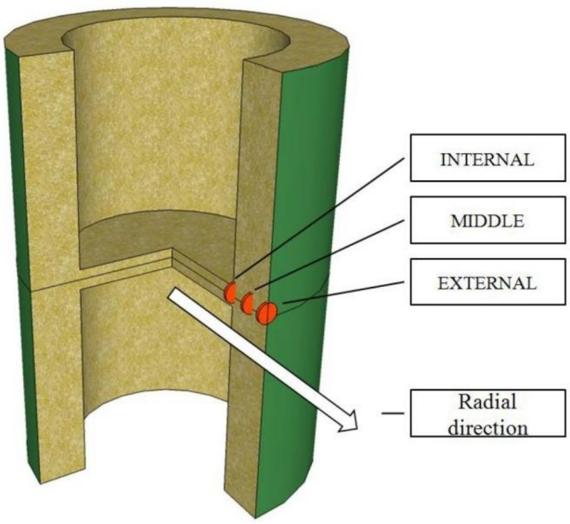


Fig. 5. Specific heat capacity of node bamboo specimens in the radial direction.

In the tangential direction, Moso bamboo specimens were cut from four representative positions. The azimuth between two adjacent positions is 90°. Three specimens were measured at each position. The average specific heat capacity values of four positions present an irregular trend. No specific gradient is found in tangential direction. See Fig. 6 and Fig. 7.

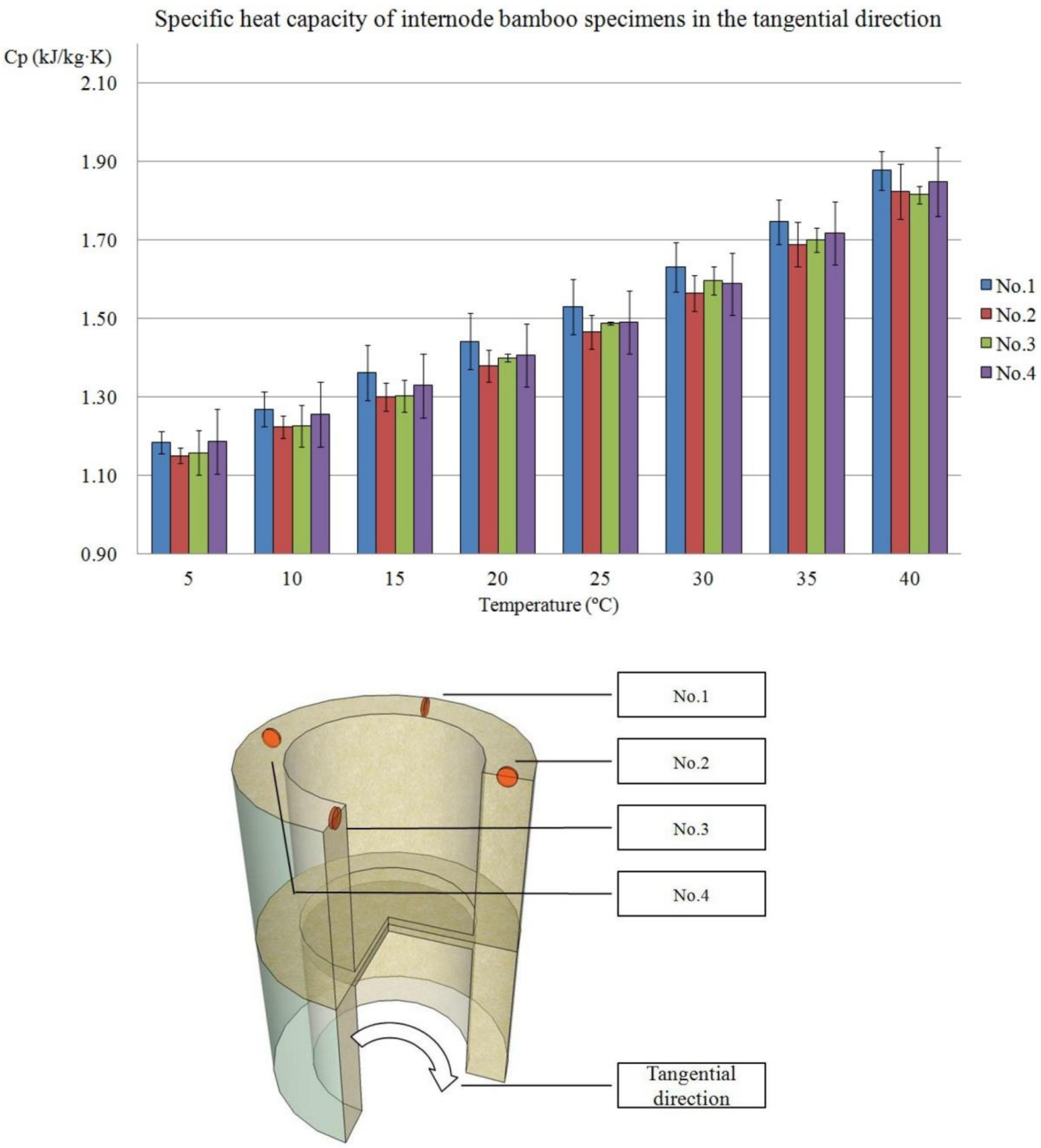


Fig. 6. Specific heat capacity of internode bamboo specimens in the tangential direction.

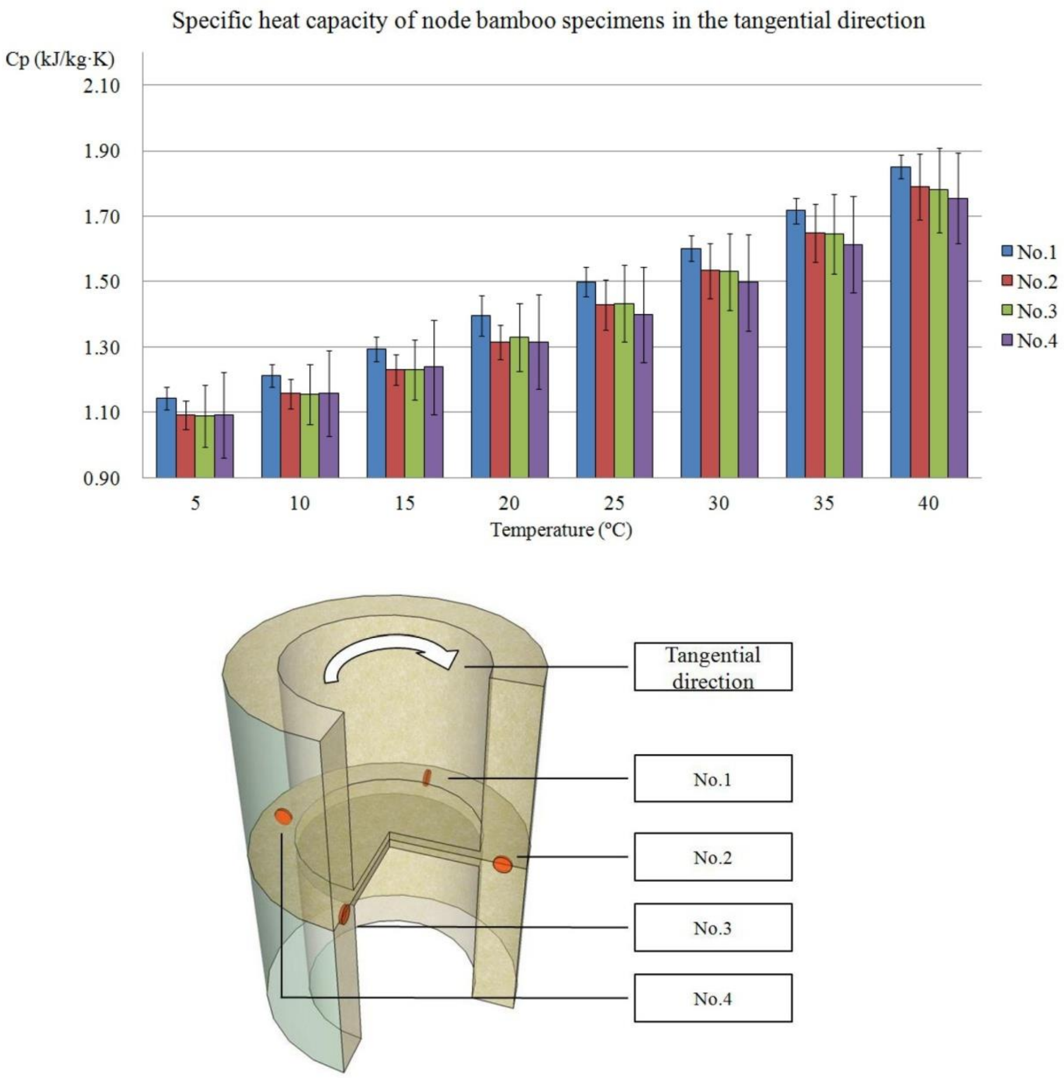


Fig. 7. Specific heat capacity of node bamboo specimens in the tangential direction.

In the longitudinal direction, specimens were cut from three positions. The distance between two adjacent positions is 3±1 mm at node part and 10±1 mm at internode part respectively. This distance is determined by the length of node part and internode part of bamboo culms. Three specimens were prepared at each position for specific heat capacity measurement. See Fig. 8 and Fig. 9.

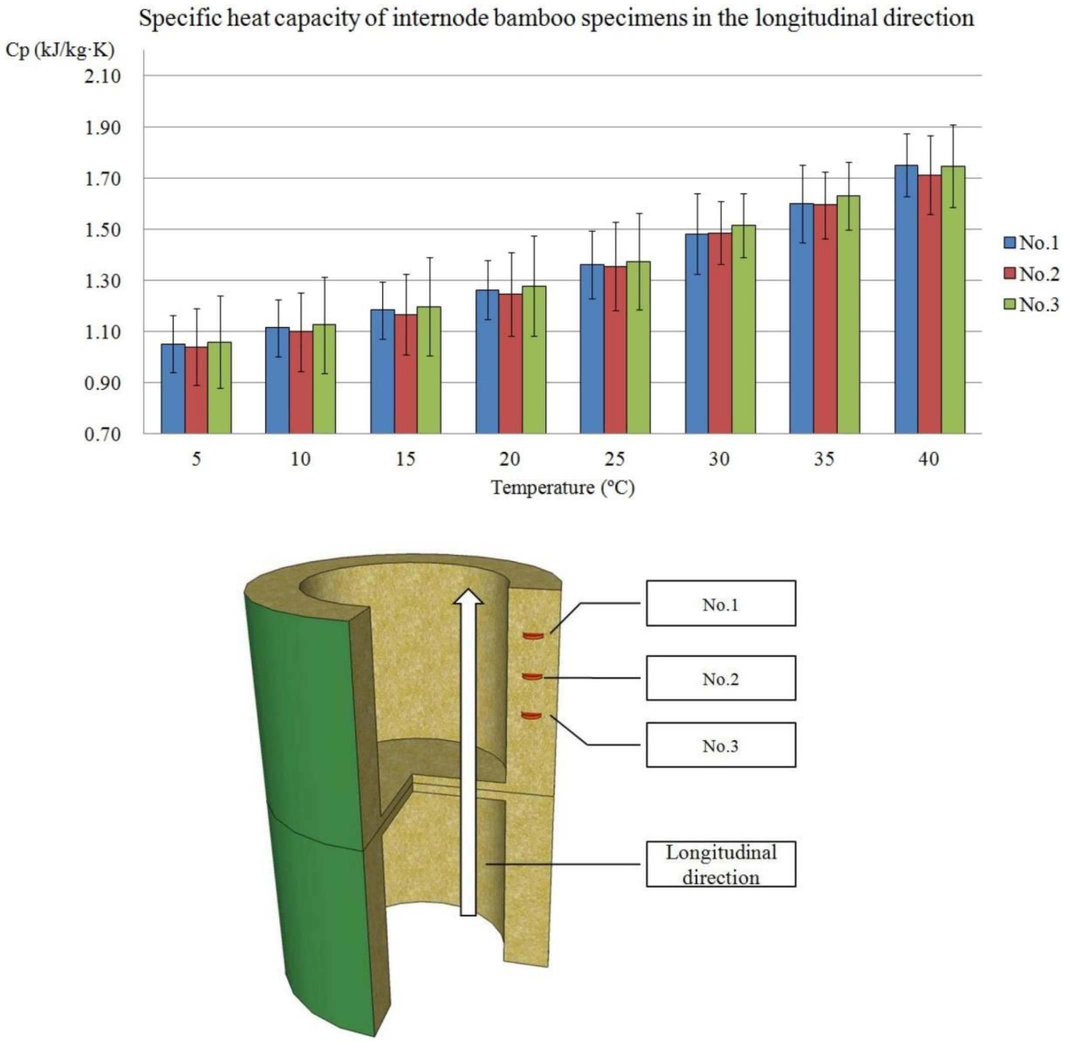


Fig. 8. Specific heat capacity of internode bamboo specimens in the longitudinal direction.

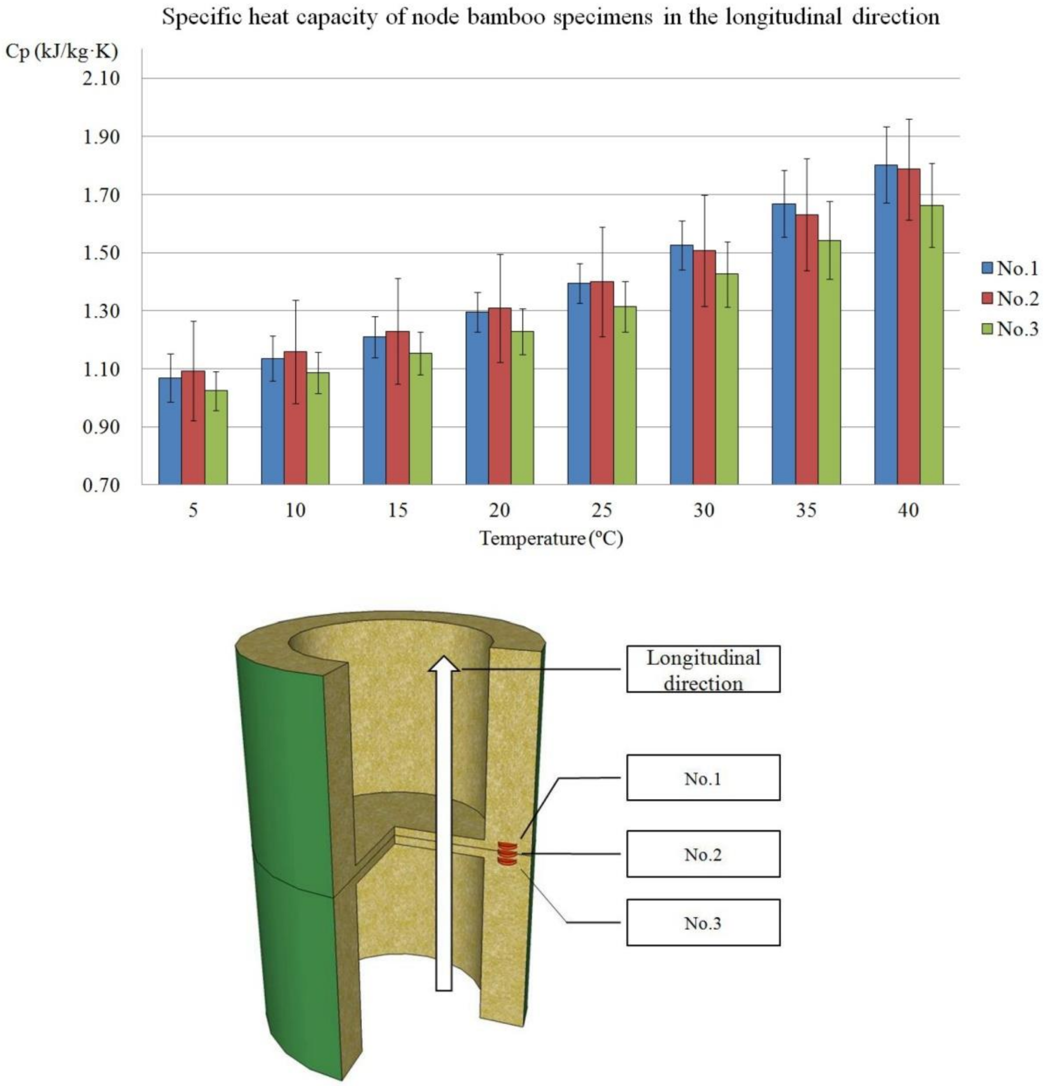


Fig. 9. Specific heat capacity of node bamboo specimens in the longitudinal direction.

3.2 Typical results summery

The average specific heat capacity results at 25 °C are compared in Fig. 10.

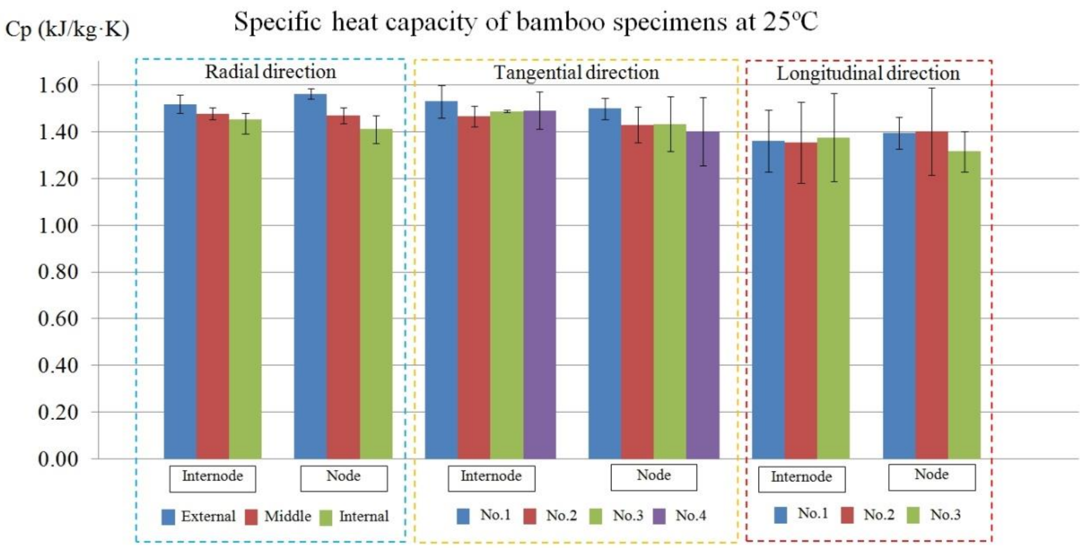


Fig. 10. Average specific heat capacity comparison at 25 °C.

In the radial direction, the average specific heat capacity values of both indernode and nodes parts feature a gradient decreasing trend from the external surface to the internal surface of the bamboo culm wall. This trend is not discovered in the tangential and longitudinal direction. In the radial and tangential direction, majority of specimens from node parts show higher standard deviation than internode parts. In the longitudinal direction, only the No.2 specimen from the node part presents a higher standard deviation range than the internode part of bamboo specimens. The average specific heat capacity values in longitudinal direction are lower than the values in the radial direction and tangential direction. The results in table 1 indicate that the average specific heat capacity values are lower than 1.40 kJ/kg·K in the longitudinal direction. The values in the radial direction and tangential direction are higher than 1.40 kJ/kg·K.

Specific heat capacity at 25 °C (kJ/kg·K)		Radial direction			Tangential direction				Longitudinal direction		
		External	Middle	Internal	No.1	No.2	No.3	No.4	No.1	No.2	No.3
Internode	Average	1.52	1.48	1.45	1.53	1.47	1.49	1.49	1.36	1.35	1.37
	Maximum	1.55	1.50	1.48	1.61	1.51	1.49	1.58	1.48	1.47	1.51
	Minimum	1.48	1.45	1.42	1.48	1.42	1.48	1.44	1.22	1.16	1.16
	SD	0.04	0.02	0.03	0.07	0.04	0.004	0.08	0.13	0.17	0.19
Node	Average	1.56	1.47	1.41	1.50	1.43	1.43	1.40	1.40	1.40	1.32
	Maximum	1.58	1.51	1.48	1.55	1.49	1.56	1.53	1.46	1.56	1.38
	Minimum	1.54	1.44	1.36	1.47	1.34	1.33	1.24	1.32	1.20	1.22
	SD	0.02	0.03	0.06	0.05	0.08	0.12	0.15	0.07	0.19	0.09

Table 1. Specific heat capacity results at 25 °C.

3.3 Discussion

All results demonstrate that the specific heat capacity of the bamboo specimens increases with temperature. This phenomenon has been mentioned in many papers on wood (Volbehr 1896, Beall 1968, Koch 1968, and Simpson and Tenwolde 1999). As aforementioned, the measured specific heat capacity is an equivalent value of many different phases due to the morphological complexity of biological materials. For example, the equivalent specific heat capacity of the bamboo can be described by Equation 2.

$$C_p = C_{pB} + C_{pL} + C_{pG} \qquad \text{Equation 2}$$

C_p: Total specific heat capacity (kJ/kg·K)
C_{pB}: Specific heat capacity of the bamboo solid phase (kJ/kg·K)
C_{pL}: Specific heat capacity of the liquid phase, e.g. water. (kJ/kg·K)
C_{pG}: Specific heat capacity of the gas phase, e.g. water vapour and air. (kJ/kg·K)

In this study, the specimens were treated to eliminate the water. The absorbed water during the loading process of specimens was assumed to be negligible. The total specific heat capacity mainly includes two phases, one is the bamboo solid phase, and the other is the dry air phase. Although the specific heat capacity of the air increases with the temperature, from 5 °C to 40 °C values are confined to the narrow range of 1.007 to 1.008 kJ/kg·K. Therefore, the air phase can be regarded as a constant component of the total specific heat capacity value. The bamboo solid phase can be regarded as the component in which the specific heat capacity increases with temperature.

T-tests were conducted to evaluate the significance of the specific heat capacity difference between the internode specimens and node specimens. The significance probability (Sig.) results indicated that the specific heat capacity difference between the internode specimens and node specimens is not significant (See Table 2). Analysis of variance (ANOVA) was made to indentify the significance of the specific heat capacity among the cutting positions. The results indicated that significant differences only exist at radial direction. It is apparent that the specific heat capacity difference between the external position and internal position is significant. For internode specimens, the specific heat capacity in the middle position showed no significant difference when they compared with specimens in the external position and internal position respectively. For node specimens, the specific heat capacity in the middle position shows no significant difference when they compare with specimens in the internal position. This fact implies that non-linear specific heat capacity values distribute from the external side to the internal side of the bamboo culm wall at both internode and node parts (See Table 3).

Independent Samples Test										
		Levene's Test for Equality of Variances		T-test for Equality of Means						
		F	Sig.	t	df	Sig. 2-tailed	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference Lower	Upper
External Radial	Equal variances assumed	0.953	0.384	-1.724	4	0.160	-0.04400	0.02553	-0.11487	0.02687
	Equal variances not assumed			-1.724	3.220	0.177	-0.04400	0.02553	-0.12218	0.03418
Middle Radial	Equal variances assumed	0.681	0.456	0.302	4	0.778	0.00733	0.02431	-0.06016	0.07482
	Equal variances not assumed			0.302	3.628	0.779	0.00733	0.02431	-0.06298	0.07765
Internal Radial	Equal variances assumed	2.057	0.225	1.053	4	0.352	0.04067	0.03863	-0.06659	0.14793
	Equal variances not assumed			1.053	2.947	0.371	0.04067	0.03863	-0.08354	0.16488
No.1 Tangential	Equal variances assumed	1.125	0.349	0.647	4	0.553	0.03100	0.04789	-0.10198	0.16398
	Equal variances not assumed			0.647	3.432	0.558	0.03100	0.04789	-0.11113	0.17313
No.2 Tangential	Equal variances assumed	1.783	0.253	0.716	4	0.513	0.03633	0.05072	-0.10448	0.17714
	Equal variances not assumed			0.716	3.152	0.523	0.03633	0.05072	-0.12075	0.19341
No.3 Tangential	Equal variances assumed	6.074	0.069	0.806	4	0.465	0.05433	0.06739	-0.13278	0.24145
	Equal variances not assumed			0.806	2.004	0.505	0.05433	0.06739	-0.23505	0.34372
No.4 Tangential	Equal variances assumed	0.937	0.388	0.945	4	0.398	0.09067	0.09589	-0.17558	0.35691
	Equal variances not assumed			0.945	3.095	0.412	0.09067	0.09589	-0.20930	0.39063
No.1 Longitudinal	Equal variances assumed	1.497	0.288	-0.401	4	0.709	-0.03433	0.08560	-0.27200	0.20333
	Equal variances not assumed			-0.401	2.998	0.715	-0.03433	0.08560	-0.30687	0.23820
No.2 Longitudinal	Equal variances assumed	0.007	0.939	-0.314	4	0.769	-0.04633	0.14768	-0.45636	0.36369
	Equal variances not assumed			-0.314	3.973	0.770	-0.04633	0.14768	-0.45747	0.36481
No.3 Longitudinal	Equal variances assumed	3.199	0.148	0.492	4	0.648	0.05900	0.11981	-0.27365	0.39165
	Equal variances not assumed			0.492	2.815	0.658	0.05900	0.11981	-0.33690	0.45490

Table 2. T-test of the specific heat capacity of bamboo specimens

	Compare groups		Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Radial direction at internode part	external	middle	0.04100	0.02565	0.161	-0.0218	0.1038
		internal	0.06700	0.02565	0.040	0.0042	0.1298
	middle	external	-0.04100	0.02565	0.161	-0.1038	0.0218
		internal	0.02600	0.02565	0.350	-0.0368	0.0888
	internal	external	-0.06700	0.02565	0.040	-0.1298	-0.0042
		middle	-0.02600	0.02565	0.350	-0.0888	0.0368
Radial direction at node part	external	middle	0.09233	0.03414	0.035	0.0088	0.1759
		internal	0.15167	0.03414	0.004	0.0681	0.2352
	middle	external	-0.09233	0.03414	0.035	-0.1759	-0.0088
		internal	0.05933	0.03414	0.133	-0.0242	0.1429
	internal	external	-0.15167	0.03414	0.004	-0.2352	-0.0681
		middle	-0.05933	0.03414	0.133	-0.1429	0.0242
Tangential direction at internode part	No. 1	No. 2	0.06433	0.04663	0.205	-0.0432	0.1719
		No. 3	0.04233	0.04663	0.390	-0.0652	0.1499
		No. 4	0.03933	0.04663	0.423	-0.0682	0.1469
	No. 2	No. 1	-0.06433	0.04663	0.205	-0.1719	0.0432
		No. 3	-0.02200	0.04663	0.650	-0.1295	0.0855
		No. 4	-0.02500	0.04663	0.606	-0.1325	0.0825
	No. 3	No. 1	-0.04233	0.04663	0.390	-0.1499	0.0652
		No. 2	0.02200	0.04663	0.650	-0.0855	0.1295
		No. 4	-0.00300	0.04663	0.950	-0.1105	0.1045
	No. 4	No. 1	-0.03933	0.04663	0.423	-0.1469	0.0682
		No. 2	0.02500	0.04663	0.606	-0.0825	0.1325
		No. 3	0.00300	0.04663	0.950	-0.1045	0.1105
Tangential direction at node part	No. 1	No. 2	0.06967	0.08442	0.433	-0.1250	0.2643
		No. 3	0.06567	0.08442	0.459	-0.1290	0.2603
		No. 4	0.09900	0.08442	0.275	-0.0957	0.2937
	No. 2	No. 1	-0.06967	0.08442	0.433	-0.2643	0.1250
		No. 3	-0.00400	0.08442	0.963	-0.1987	0.1907
		No. 4	0.02933	0.08442	0.737	-0.1653	0.2240
	No. 3	No. 1	-0.06567	0.08442	0.459	-0.2603	0.1290
		No. 2	0.00400	0.08442	0.963	-0.1907	0.1987
		No. 4	0.03333	0.08442	0.703	-0.1613	0.2280
	No. 4	No. 1	-0.09900	0.08442	0.275	-0.2937	0.0957
		No. 2	-0.02933	0.08442	0.737	-0.2240	0.1653
		No. 3	-0.03333	0.08442	0.703	-0.2280	0.1613
Longitudinal direction at internode part	No. 1	No. 2	0.00667	0.13569	0.962	-0.3254	0.3387
		No. 3	-0.01300	0.13569	0.927	-0.3450	0.3190
	No. 2	No. 1	-0.00667	0.13569	0.962	-0.3387	0.3254
		No. 3	-0.01967	0.13569	0.890	-0.3517	0.3124
	No. 3	No. 1	0.01300	0.13569	0.927	-0.3190	0.3450
		No. 2	0.01967	0.13569	0.890	-0.3124	0.3517
Longitudinal direction at node part	No. 1	No. 2	-0.00533	0.10287	0.960	-0.2571	0.2464
		No. 3	0.08033	0.10287	0.465	-0.1714	0.3321
	No. 2	No. 1	0.00533	0.10287	0.960	-0.2464	0.2571
		No. 3	0.08567	0.10287	0.437	-0.1661	0.3374
	No. 3	No. 1	-0.08033	0.10287	0.465	-0.3321	0.1714
		No. 2	-0.08567	0.10287	0.437	-0.3374	0.1661

Table 3. ANOVA of the specific heat capacity of bamboo specimens

In addition, the specific heat capacity results in the longitudinal direction are lower than the other two directions. The morphological structure in backscattered electron (BSE) images of Moso bamboo may explain this variation (See Fig. 11). Fig. 10a is the section view of the longitudinal specimens. Fig. 11b is the section view of the radial specimens. Fig. 11c is the section view of the tangential specimens. Fig. 10d is a high magnification backscattered electron image of the ground tissue cell.

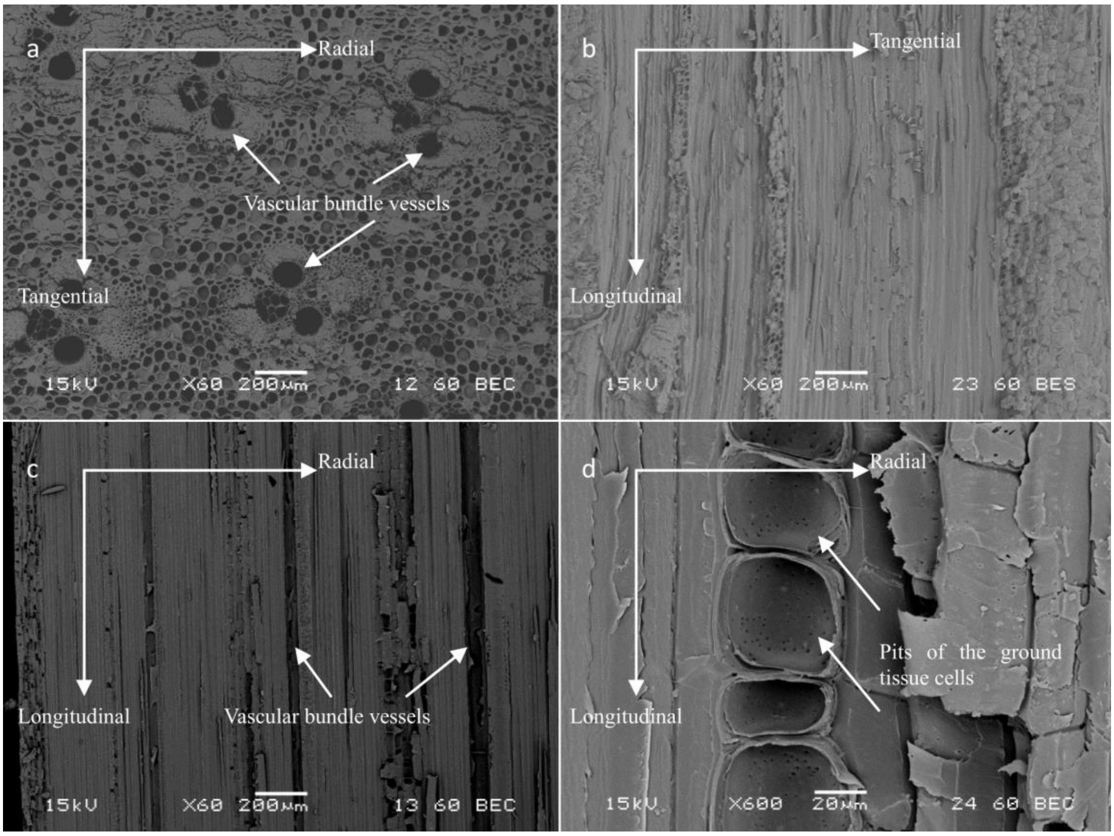


Fig. 11. (a) The radial-tangential section view of the Moso bamboo BSE image. (b) The tangential-longitudinal section view of the Moso bamboo BSE image. (c) The radial -longitudinal section view of the Moso bamboo BSE image. (d) The radial -longitudinal section view of the Moso bamboo BSE image at a high magnification.

In the DSC measurement process, when the heat flow is along the longitudinal direction, the convective heat lost may be higher than the other two directions. The vascular bundles provide many straight tunnels for the air ventilation. The specific heat capacity can also be considered as the parameter to describe the heat sink ability when the energy is input. Relatively small pits, holes and tightly arranged cells could be assumed as the features of higher specific heat capacity because these features provide considerable barriers to convective heat lost. This assumption can explain why the results of the external specimens in the radial direction possess the highest specific values while specimens in the longitudinal direction possess lower specific heat capacity.

4. Conclusions

The specific heat capacity of the Moso bamboo specimens were measured by DSC. The measurements were conducted in all directions of the cylindrical coordinates system at both internode parts and node parts. All results demonstrate a feature that the specific heat capacity of the bamboo specimens increases with the temperature. Relatively small pits, holes and tightly arranged cells result in higher specific heat capacity. In the radial direction, the results for both internode and node parts indicate that the specific heat capacity decreases from the external surface to the internal surface. In tangential and longitudinal direction, average specific heat capacity values present an irregular trend. No specific gradient are found in these two directions.

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